



Committee on Earth Observation Satellites

CEOS AC-VC Whitepaper

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Chapters

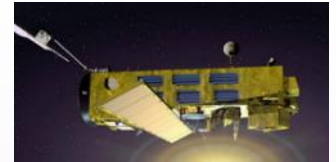
Contributions from participants at the CEOS SIT and CEOS AC-VC meetings were incorporated into the White Paper structure:

Executive Summary

1. Introduction
2. Using atmospheric GHG measurements to improve inventories
3. Space-based GHG measurement capabilities and near term plans
4. Lessons Learned from SCIAMACHY, GOSAT and OCO-2
5. Integrating GHG Satellites into Operational Constellations
6. Towards an operational constellation measuring anthropogenic CO₂ emissions
7. The Transition from Science to Operations
8. Conclusions

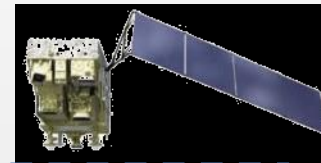
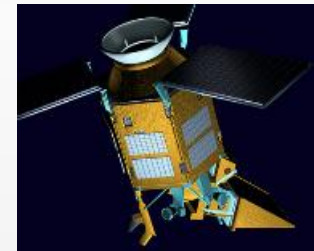


- **SCIAMACHY (2002-2012)** – First sensor to measure O_2 , CO_2 , and CH_4 using reflected NIR/SWIR sunlight
 - Regional-scale maps of X_{CO_2} and X_{CH_4} over continents
- **GOSAT (2009 ...)** – First Japanese GHG satellite
 - FTS optimized for high spectral resolution over broad spectral range, yielding CO_2 , CH_4 , and chlorophyll fluorescence (SIF)
- **OCO-2 (2014 ...)** – First NASA satellite to measure O_2 and CO_2 with high sensitivity, resolution, and coverage
 - High resolution imaging grating spectrometer small ($< 3 \text{ km}^2$) footprint and rapid sampling (10^6 samples/day)
- **TanSat (2016 ...)** - First Chinese GHG satellite
 - Imaging grating spectrometer for O_2 and CO_2 bands and cloud & aerosol Imager
 - In-orbit checkout formally complete in August 2017

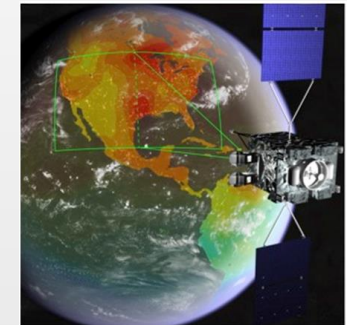
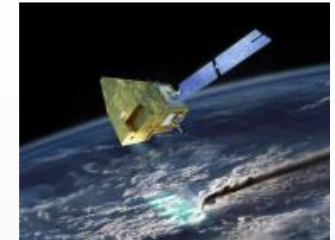


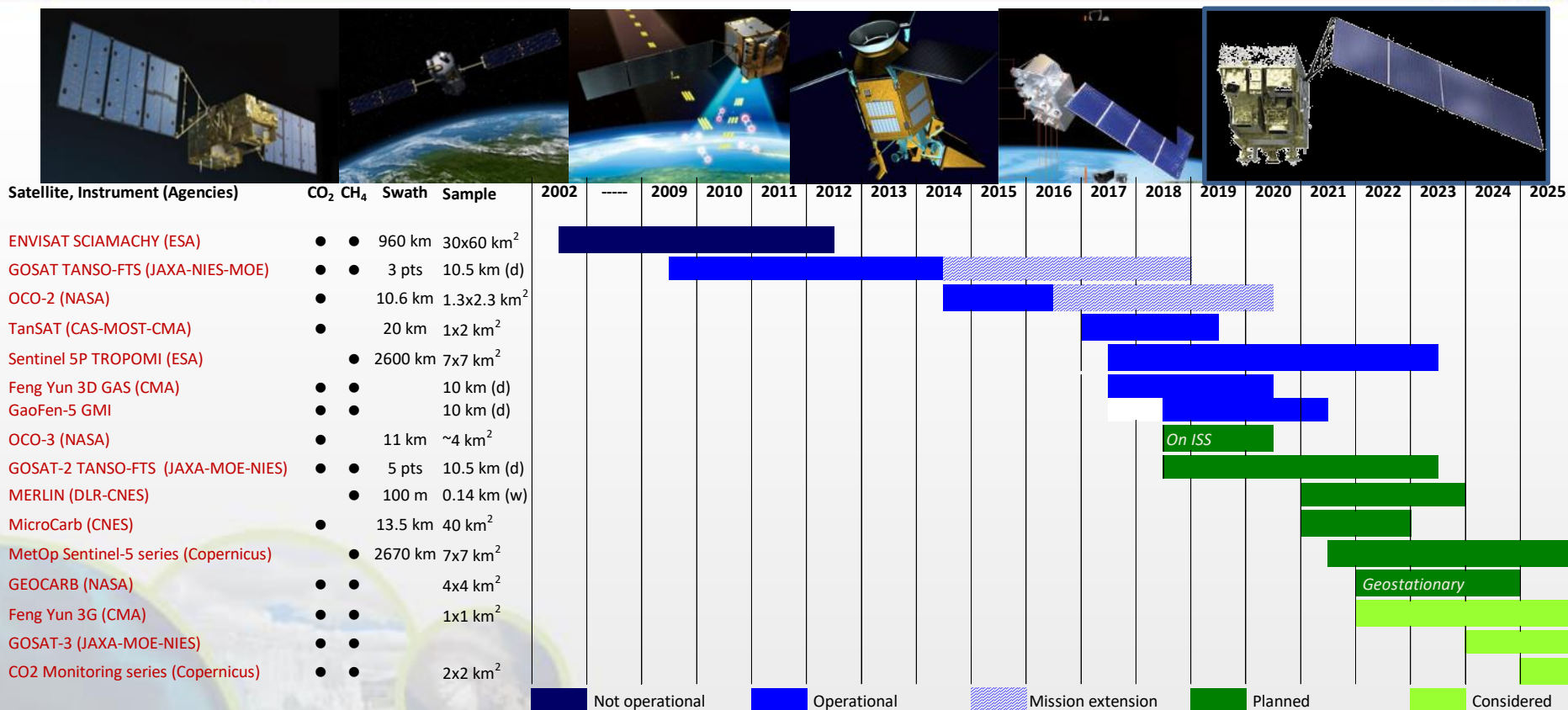


- **Feng Yun 3D (2017)** – Chinese GHG satellite on an operational meteorological bus
 - GAS FTS for O₂, CO₂, CH₄, CO, N₂O, H₂O
- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
 - TROPOMI measures O₂, CH₄ (1%), CO (10%), NO₂, SIF
 - Imaging at 7 km x 7 km resolution, daily global coverage
- **Gaofen 5 (2018)** - 2nd Chinese GHG Satellite
 - Spatial heterodyne spectrometer for O₂, CO₂, and CH₄
- **GOSAT-2 (2018)** – Japanese 2nd generation satellite
 - CO as well as CO₂, CH₄, with improved precision (0.125%), and active pointing to increase number of cloud free observation
- **OCO-3 (2019)** – NASA OCO-2 spare instrument, on ISS
 - First CO₂ sensor to fly in a low inclination, precessing orbit



- **CNES/UK MicroCarb (2021+)** – compact, high sensitivity
 - Imaging grating spectrometer for $O_2 A$, $O_2^1\Delta_g$, and CO_2
 - ~1/2 of the size, mass of OCO-2, with 4.5 km x 9 km footprints
- **CNES/DLR MERLIN (2021+)** - First CH_4 LIDAR (IPDA)
 - Precise (1-2%) X_{CH_4} retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH_4 budgets
- **NASA GeoCarb (2022*)** – First GEO GHG satellite
 - Imaging spectrometer for X_{CO_2} , X_{CH_4} , X_{CO} and SIF
 - Stationed above $\sim 85^\circ W$ to view North/South America
- **Sentinel 5A,5B,5C (2022)** - Copernicus operational services for air quality and CH_4
 - Daily global maps of X_{CO} and X_{CH_4} at $< 8\text{ km} \times 8\text{ km}$





- A broad range of GHG missions will be flown over the next decade.
- Most are “**science**” missions, designed to identify optimal methods for measuring CO₂ and CH₄, not “**operational**” missions designed to deliver policy relevant GHG products focused on anthropogenic emissions

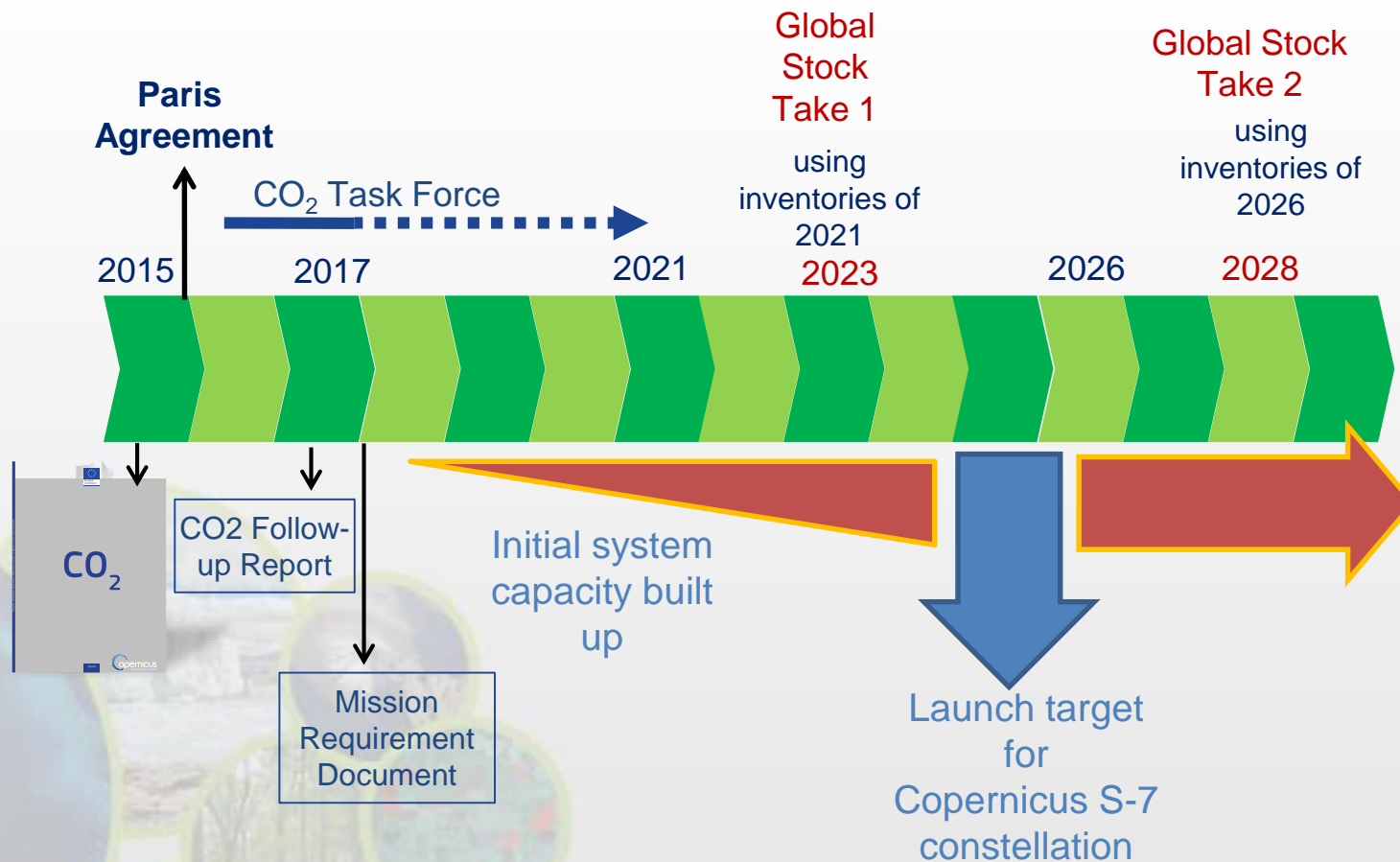


The CO₂ and CH₄ measurement requirements in the 2011 update for the Global Climate Observing System (GCOS) Systematic Observation Requirements for Satellite-Based Data Products for Climate (GCOS, 2011) and GCOS 2016 Implementation Plan (GCOS, 2016) were adopted as targets for a future GHG constellation.

Variable / Parameter	Horizontal Resolution	Vertical Resolution	Temporal Resolution	Accuracy	Stability/Decade*	Stability/Decade**
Tropospheric CO ₂ column	5-10km	N/A	4 h	1 ppm	0.2 ppm	1.5 ppm
Tropospheric CO ₂	5-10 km	5 km	4 h	1 ppm	0.2 ppm	1.5 ppm
Tropospheric CH ₄ column	5-10 km	N/A	4 h	10 ppb	2 ppb	7 ppb
Tropospheric CH ₄	5-10 km	5 km	4 h	10 ppb	2 ppb	0.7 ppb
Stratospheric CH ₄	100-200 km	2 km	Daily	5%	0.30%	0.30%

* from GCOS 2011

** from GCOS 2016





The accuracy, precision, resolution, and coverage requirements could be achieved with a constellation that incorporates

- A constellation of 3 (or more) satellites in LEO with
 - A broad (> 200) km swath with a mean footprint size $< 4 \text{ km}^2$
 - A single sounding random error near 0.5 ppm, and vanishing small regional scale bias ($< 0.1 \text{ ppm}$) over $> 80\%$ of the sunlit hemisphere
 - One (or more) satellites carrying ancillary sensors (CO , NO_2 , CO_2 and/or CH_4 Lidar)
- A constellation with 3 (or more) GEO satellites
 - Monitor diurnally varying processes (e.g. rush hours, diurnal variations in the biosphere)
 - Stationed over Europe/Africa, North/South America, and East Asia
- This constellation could be augmented with one or more HEO satellites to monitor carbon cycle changes in the high arctic

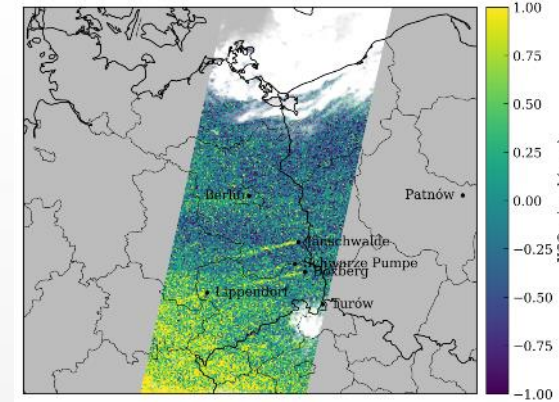
Future LEO GHG Constellations in the Planning Stages



- Copernicus CO₂ Sentinel (2025+)

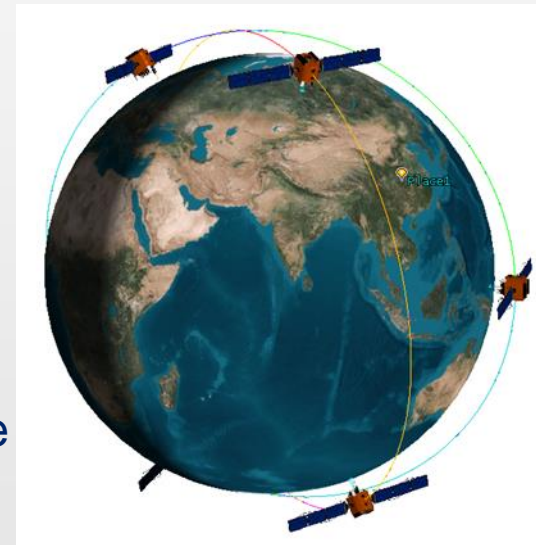
- 3 or 4 LEO satellites in an operational GHG constellation
- Primary instruments measure O₂ (0.76 μm A-band), CO₂ (1.61 and 2.06 μm), CH₄ (1.67 μm) and NO₂ (0.450 μm) at a spatial resolution of 2 km x 2 km along a 200-300 km swath
- A dedicated cloud/aerosol instrument is also under consideration

X_{CO_2} ($\sigma = 0.5$ ppm)



- TanSat-2 Constellation

- 6 satellites, with 3 flying in morning sun-synchronous orbits and 3 flying in afternoon sun-synchronous orbits
- primary GHG instrument on each satellite with measure CO₂ (1.61 and 2.06 μm), CH₄ and CO (2.3 μm) as well as the O₂ A-band (0.76 μm) across a 100-km cross-track swath



TanSat Constellation



- Because of the unprecedented requirements for precision and accuracy, the space based elements of the an operational GHG constellation architecture must be accompanied by
 - Rigorous pre-launch and on-orbit measurement calibration and product validation methods that evolve to meet emerging needs
 - Continuous refinements in remote sensing retrieval and flux inversion modeling methods that improve the products over time
- CEOS could play an essential role in coordinating these activities among its partner agencies
- Any operational architecture will also have to address
 - orbit and mission coordination, data distribution, data exchange, and data format requirements
 - Training and capacity building and public outreach will be needed to fully exploit the value of the space based GHG measurements
- CEOS should collaborate with CGMS and other operational organizations to foster the development of these capabilities